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Preliminary Efforts to Couple TETRAD with Geophysics Models

G. M. Shook
J. L. Renner

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PRELIMINARY EFFORTS TO COUPLE TETRAD WITH GEOPHYSICS MODELS

G. Michael Shook and Joel L. Renner

Idaho National Engineering and Environmental Laboratory
PO Box 1625, Idaho Falls, ID 83415-2107
Ook@inel.gov, jlrenner@inel.gov

ABSTRACT

The Geothermal Program at Idaho National Engineering and Environmental Laboratory is enhancing our reservoir simulation capabilities by writing new subroutines within TETRAD that write necessary files for use with SAIC's geophysics models, including DC Resistivity, SP, and microgravity. This is part of long-term efforts to develop reservoir models that take advantage of various observations that are – or can be – made on both existing fields or during exploration efforts. These new routines will be made available to the TETRAD user community in 2002 through the next release of TETRAD 2002.

INTRODUCTION

Over the last several years, various papers have appeared in the literature that show reservoir simulation results being used in geophysical model postprocessing for improved reservoir management (e..g, Nakanishi et al., 2000; Pritchett et al., 2000). These efforts have grown from projects funded by the New Energy and Industrial Development Organization (NEDO, a Japanese Government agency). Through these efforts, a number of geophysical postprocessors have been developed that take results from reservoir simulation (primarily Star; Pritchett, 1995) and predict what changes in geophysical properties might be observable for a given reservoir management scheme. In theory, use of reservoir/geophysics models can provide a "positive feedback" that can be used to optimize field operations.

Several months ago, in conversations with the geophysical models' authors, INEEL researchers obtained permission to use these models for internal research purposes. The goal of this work was to write interfaces between our existing reservoir model, TETRAD (Vinsome and Shook, 1993) and the geophysical models. The resulting updated version of TETRAD would then be available to other TETRAD users from the code distributor, ADA International. SAIC's geophysical models remain private, and would be either purchased from or leased through SAIC.

This report describes the efforts made to date in writing interfaces between TETRAD and STAR's geophysics postprocessors. To date, all code modifications are complete, and test cases have been run using the DC resistivity, SP, and microgravity models. Final validation of the work is ongoing, and is expected to be completed in Spring 2002. The revised TETRAD code will be available for release thereafter.

TETRAD CODE REVISIONS

In writing an interface between TETRAD and the geophysical models, several new features were implemented in TETRAD. Specifically changes were required that allow rock properties to be defined on a "regional" basis. The current implementation is such that a "rock type" is defined in the input file, and its regional distribution is specified. TETRAD then checks to see that all petrophysical properties within that rock domain are similar. A future version will allow all petrophysical properties to be defined with this new keyword ('ROXTYP') as is done in other geothermal simulators in use.

A second keyword was added to TETRAD that indicates a "Geophysics output" file is desired by the user. Upon reading 'GEOPHY' and the print frequency (every NPRGEO) of output desired, TETRAD opens an output file with a ".GEO" extension, loads the relevant petrophysical properties in storage, and verifies that all grid blocks within that rock type have identical properties (k, φ, Cp, etc.). The output file is opened, and static data is printed. Then, during the course of the simulation, dynamic data required by the geophysics models (e.g., phase volumes, component and phase fluxes, etc.) are written to the file every NPRGEO time steps, in addition to times explicitly stated in the input deck. Also, new subroutines (taken in part from the STAR source code) were added to TETRAD to calculate and output reservoir conditions required by the geophysics models. The balance of the code modifications required were conversions between

units, renumbering phases and spatial indices, adding new storage vectors for input, and the like, and are transparent to the user.

New keywords and subroutines required to take advantage of SAIC's geophysics models are summarized in Table 1 below. An example of the top portion of the new *.GEO file is given in Table 2.

RESTRICTIONS OF VERSION 1

Because of various differences between the two reservoir simulation codes from which the geophysics data is generated, several restrictions within TETRAD are required. The most significant of these are given below.

- no 2-D cross section simulations
- no dual porosity
- permeability, porosity, and thermal conductivity of rock is not a function of pressure or temperature.
- No solid precipitation

These will be removed in Version 2, which is expected to be completed later in 2002.

SUMMARY AND FUTURE WORK

Testing and validation of Version 1 of this interface will be completed in February, 2002, and will be made available for distribution with the release of TETRAD 2002. Version 2 will be completed by Summer 2002 will be forwarded to ADA International for incorporation in the next release of TETRAD. An internal INEEL report will be completed documenting the changes necessary in TETRAD, and will present validation problems that demonstrate the utility of the enhanced simulation package.

The linking of TETRAD results with SAIC's geophysics models (and others as the opportunity arises) is the first stage of an ongoing project at INEEL to enhance reservoir simulation capability. We have also begun the second part of this project, which is to develop an inverse model for reservoir parameter estimation (TET^{-1}). The first version of is expected to be completed late this year. The third stage of the project is to develop a model that performs a joint inversion of TETRAD and geophysics models ($TETGEO^{-1}$) by 2003.

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Table 1. Summary of Key Changes to TETRAD

Subroutines	Keywords	Description
	'GEOPHY' NPRGEO	Opens an output file for geophysics output (*.GEO) and writes output every NPRGEO timesteps
	'ROXTYP'	Reads and stores rock types on a regional basis for each rock type
GPHY		Tests for constancy of petrophysical properties for each rock type, writes *.GEO header information
STATIC		Calculates grid boundaries, rock volumes and mass, etc., and prints static information to *.GEO
DYNAMIC		Calculates all required output for *.GEO every NPRGEO steps from existing TETRAD properties (e.g., mass fluxes from phase molar fluxes) and prints

REFERENCES

Nakanishi, S., J.W. Pritchett, and S. Yamazawa, 2000, "Numerical Simulation of Changes in Microgravity and Electrokinetic Potentials Associated with the Exploitation of the Onikobe Geothermal Field, Miyagi Prefecture, Japan," Proc. 25th Workshop on Geothermal Reservoir Engineering, Jan. 24-26, Stanford, Ca.

Pritchett, J.W., 1995, "STAR: A geothermal reservoir simulation system," Proc. World Geothermal Congress 1995, Florence, pp. 2959-2963.

Pritchett, J.W., J. Stevens, P. Wannamaker, S. Nakanishi, and S. Yamazawa, 2000, "Theoretical Feasiblity Studies of Reservoir Monitoring Using Geophysical Surfey Techniques," Proc. World Geothermal Congress, Kyushu-Tohoku, pp. 2803-2808.

Vinsome, P.K.W. and G.M. Shook, 1993, "Multi-purpose simulation," J. Petroleum and Engineering, 9, pp 29-38.

Table 2. Example (abridged) output from TETRAD for Geophysics Models (TEST.GEO).

```
 _____________________________________________________
|                                                     |
|                                                     |
|    #######   #########  #########  #######         |
|   #########  #########  #########  ########        |
|   ##            ###     ##     ##  ##     ##       |
|   ########      ###     ##     ##  ########        |
|    ########     ###     #########  #######         |
|          ##     ###     #########  ##   ##         |
|   #########     ###     ##     ##  ##    ##        |
|    #######      ###     ##     ##  ##     ##       |
|                                                     |
|                                                     |
|   G  E  O  P  H  Y  S  I  C  S     D  A  T  A      |
|                                                     |
|  Generated from a TETRAD simulation                 |
|                                                     |
|  Double precision used for all floating point       |
|                                                     |
| should consider writing tetrad version # here       |
|_____________________________________________________|


"SI" (systeme internationale) unit system employed

Total number of pore-fluid components involved = 1:
Component number 1:     WATER

Total number of dilute tracer species involved = 0:

Number of possible pore phases involved = 2:
Phase 1: Liquid
Phase 2: Vapor

Total number of geological formations involved = 5:
Formation  1  (homogeneous porous medium):                                  BASE1
    ------------------------------------------------------------------------------
--
   | Properties                              Region 1             Region 2
|
   |
|
   | Volume fraction            (dl)  1.0000000000000E+00
0.0000000000000E+00 |
   | Initial Porosity           (dl)  5.0000000000000E-02
0.0000000000000E+00 |
   | Grain density         (kg/m**3)  2.5000000000000E+03
0.0000000000000E+00 |
   | Grain heat capacity    (J/kg/K)  1.0000000000000E+03
0.0000000000000E+00 |
   | Grain thermal cond.     (W/m/K)  2.9999989440000E+00
0.0000000000000E+00 |
   | Grain expansivity         (1/K)  0.0000000000000E+00
0.0000000000000E+00 |
   | Dry expansivity           (1/K)  0.0000000000000E+00
0.0000000000000E+00 |
```

```
   | Loading bulk modulus       (Pa)  1.0000000000000E+20
0.0000000000000E+00 |
   | Unloading bulk modulus     (Pa)  1.0000000000000E+20
0.0000000000000E+00 |
   | Shear modulus              (Pa)  0.0000000000000E+00
0.0000000000000E+00 |
   | Initial permeability (1) (m**2)  9.8692300000000E-17
0.0000000000000E+00 |
   | Initial permeability (2) (m**2)  9.8692300000000E-17
0.0000000000000E+00 |
   | Initial permeability (3) (m**2)  9.8692300000000E-17
0.0000000000000E+00 |
   | Permeability coeff. "e1"   (dl)  0.0000000000000E+00
0.0000000000000E+00 |
   | Permeability coeff. "e2"   (dl)  0.0000000000000E+00
0.0000000000000E+00 |
   | Permeability coeff. "e3"   (dl)  0.0000000000000E+00
0.0000000000000E+00 |
    ------------------------------------------------------------------------
--
 … 4 other formation blocks removed    ------------------------------------
---

Problem geometry: 3-dimensional Cartesian with
        20 divisions in x-direction ("I"-index),
        20 divisions in y-direction ("J"-index), and
        20 divisions in z-direction ("K"-index)
Gravity acceleration in x-direction =  0.0000000000000E+00 m/s**2
Gravity acceleration in y-direction =  0.0000000000000E+00 m/s**2
Gravity acceleration in z-direction = -9.8100004196167E+00 m/s**2

Total number of non-void grid blocks =  8000

Grid block boundary locations in   1-index direction (meters):
 0.0000000000000E+00 9.0000000000000E+02 1.6500000000000E+03
2.2500000000000E+03
 2.7000000000000E+03 3.0000000000000E+03 3.3000000000000E+03
3.6000000000000E+03
 3.9000000000000E+03 4.2000000000000E+03 4.5000000000000E+03
4.8000000000000E+03
 5.1000000000000E+03 5.4000000000000E+03 5.7000000000000E+03
6.0000000000000E+03
 6.3000000000000E+03 6.7500000000000E+03 7.3500000000000E+03
8.1000000000000E+03
 9.0000000000000E+03

Grid block boundary locations in   2-index direction (meters):
 0.0000000000000E+00 9.0000000000000E+02 1.6500000000000E+03
2.2500000000000E+03
 2.7000000000000E+03 3.0000000000000E+03 3.3000000000000E+03
3.6000000000000E+03
 3.9000000000000E+03 4.2000000000000E+03 4.5000000000000E+03
4.8000000000000E+03
 5.1000000000000E+03 5.4000000000000E+03 5.7000000000000E+03
6.0000000000000E+03
 6.3000000000000E+03 6.7500000000000E+03 7.3500000000000E+03
8.1000000000000E+03
 9.0000000000000E+03
```

```
Grid block boundary locations in   3-index direction (meters):
 0.0000000000000E+00 2.5000000000000E+02 5.0000000000000E+02
7.5000000000000E+02
 1.0000000000000E+03 1.1250000000000E+03 1.2500000000000E+03
1.3750000000000E+03
 1.5000000000000E+03 1.6250000000000E+03 1.7500000000000E+03
1.8750000000000E+03
 2.0000000000000E+03 2.1250000000000E+03 2.2500000000000E+03
2.3750000000000E+03
 2.5000000000000E+03 2.6250000000000E+03 2.7500000000000E+03
2.8750000000000E+03
 3.0000000000000E+03

Grid Block   Block Index    Contains    Total volume of grid     Mass of rock
in
    Number   "I" "J" "K"   formation    block (cubic meters)     grid block
(kg)
      7981    1  20  20        1         2.0250000000000E+08
4.8093750000000E+11
      7982    2  20  20        1         1.6875000000000E+08
4.0078125000000E+11
        19   19   1   1        5         8.4375000000000E+07
1.4765625000000E+11
        20   20   1   1        5         1.0125000000000E+08
1.7718750000000E+11

Define:
P-bar = pore-volume-average grid block pressure (Pa),
T-bar = volume-average grid block temperature (C)
Tf = fracture-zone temperature (C)
Tm-bar = volume-average matrix region temperature (C)
Tm-min = minimum matrix region temperature (C)
Tm-max = maximum matrix region temperature (C)
Pf = fracture-zone pressure (Pa)
Pm-bar = matrix region pore-volume-average pressure (Pa)
Vt = total volume (cubic meters)
Mt = total mass (kilograms)
Vf = fracture-zone volume (cubic meters)
Mf = fracture-zone mass (kilograms)
Cf = fracture-zone mass fraction
FjP = fracture-zone mass flux in "j" direction
      at "plus-xj" perpendicular block face
      (kg/second/square meter total area)
FjM = fracture-zone mass flux in "j" direction
      at "minus-xj" perpendicular block face
      (kg/second/square meter total area)
{p"N"} = phase "N"
{c"L"} = component "L"
{t"K"} = tracer "K"

Structure of remainder of this file:

-------------------------------------
B   L   A   N   K       L   I   N   E
Cycle {first}       Time = ?? seconds
Grid Block 1            P-bar,  T-bar
Tf,Tm-bar,Tm-min,Tm-max
```

```
Pf{p1},Pm-bar{p1}
Vt{p1},Mt{p1,c1},Mt{p1,c2},Mt{p1,c3}, ...
Vf{p1},Mf{p1,c1},Mf{p1,c2},Mf{p1,c3}, ...
F1P{p1},F1M{p1},F2P{p1],F2M{p1},F3P{p1},F3M{p1}
Pf{p2},Pm-bar{p2}
Vt{p2},Mt{p2,c1},Mt{p2,c2},Mt{p2,c3}, ...
Vf{p2},Mf{p2,c1},Mf{p2,c2},Mf{p2,c3}, ...
F1P{p2},F1M{p2},F2P{p2],F2M{p2},F3P{p2},F3M{p2}
Grid Block 2            P-bar,  T-bar
.     .     .     .     .     .     .
-------------End-of-File-------------

Cycle    1    Time =-4.7336399684424E+11 seconds
Grid Block      7981 2.4538865275955E+07 1.9250000079606E+02
 1.9250000079606E+02 1.9250000079606E+02 1.9250000079606E+02
1.9250000079606E+02
 2.4538865275955E+07 2.4538865275955E+07
 1.0125000000000E+07 8.8334221040018E+09
 1.0125000000000E+07 8.8334221040018E+09
-4.7988632277914E-18 0.0000000000000E+00 0.0000000000000E+00
4.7988632277914E-18 0.0000000000000E+00 6.1737481062611E-08
 2.4538865275955E+07 2.4538865275955E+07
 0.0000000000000E+00 0.0000000000000E+00
 0.0000000000000E+00 0.0000000000000E+00
 0.0000000000000E+00 0.0000000000000E+00 0.0000000000000E+00
0.0000000000000E+00 0.0000000000000E+00 0.0000000000000E+00
Grid Block      7982 2.4538865275962E+07 1.9250000079606E+02
```